



# Performance studies of cryogenically cooled monochromator crystals under extreme heat load

L Zhang,

A.K. Freund,

T. Tschentscher,

H. Schulte-Schrepping,

ESRF

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# Outline

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- **Introduction**
- **Thermo-mechanical properties of the crystals**
- **Time structure of X-ray sources**
- **Cooling, geometry and power absorption**
- **Thermal deformation of the crystal in time-averaged mode**
- **Time-dependent temperature and thermal slope error**
- **Concluding remarks**

# Introduction

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- **In 3G light sources, silicon crystal monochromators**
  - Liquid-nitrogen cooled
  - Good performance
  - ~ heat load limits in some cases
  - Typical requested performance: thermal slope error < 10  $\mu$ rad
- **For 4G light sources, challenge in the optics design**
  - Higher power or power density
  - Time structure of X-FELs
- **Possible performance improvement**
  - Using crystal materials with lower ratio of  $\alpha/\kappa$  than silicon
  - Using enhanced cooling techniques (high  $h_{cv}$ , or low  $T_f$ )

# **Introduction - *crystal materials with low ratio of $\alpha/\kappa$***

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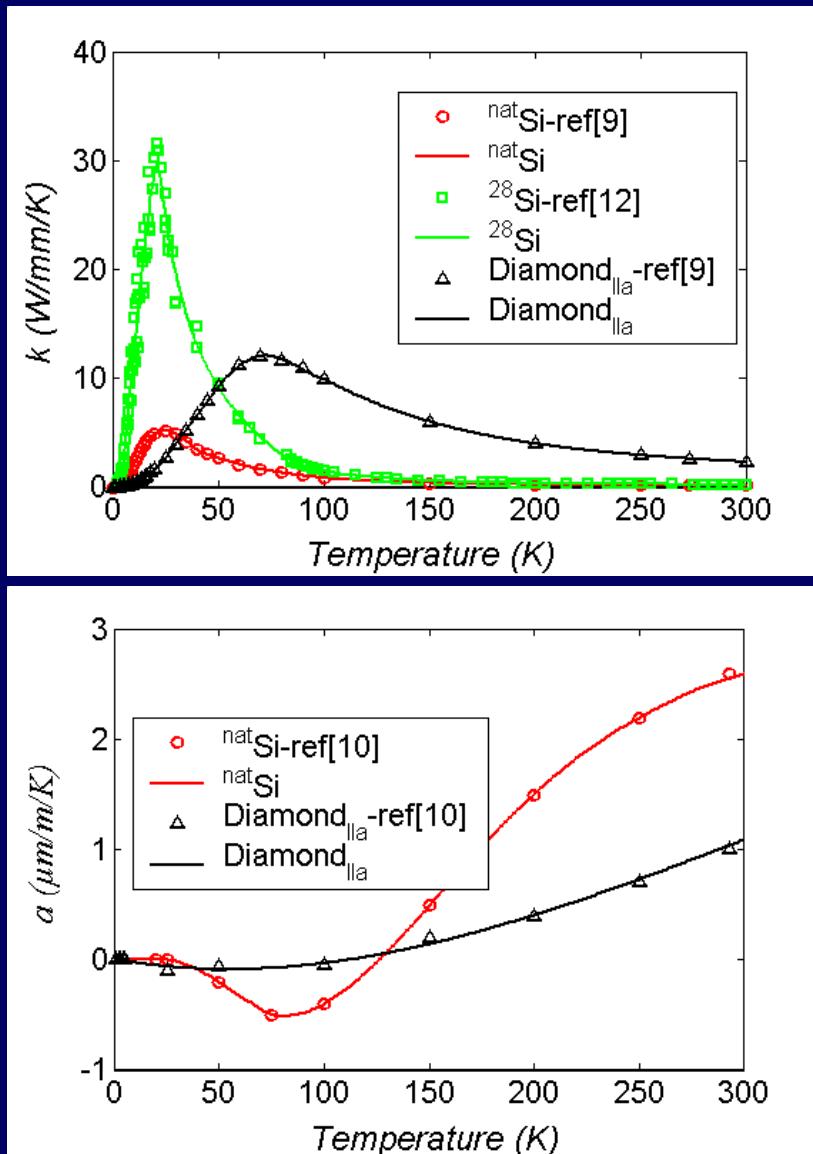
## ➤ **Single-isotope silicon-28 crystal (99.9%)**

- Three stable isotopes in natural silicon:
  - Silicon-28 : 92%
  - Silicon-29 : 4.7%
  - Silicon-30 : 3.3%
- Higher thermal conductivity than natural silicon  
( $\kappa = 30\,000 \text{ W m}^{-1} \text{ K}^{-1}$  at 20 K, 6 times higher than natural Si)
- Available, used in semiconductor industry

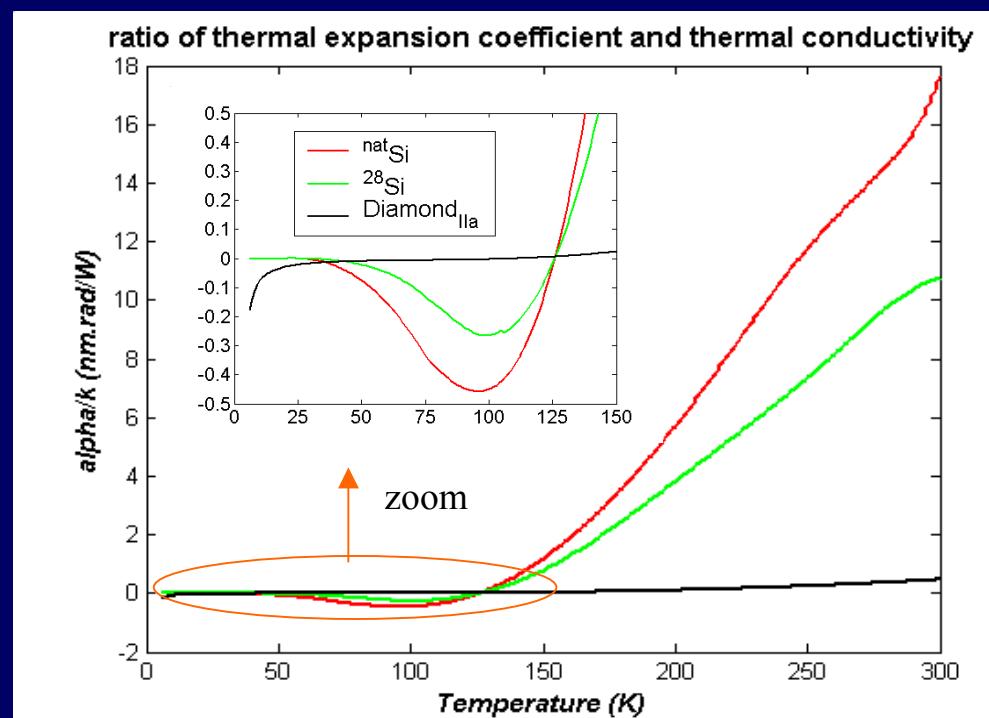
## ➤ **Diamond crystal**

- Diamond IIa, synthetic diamond available in 1 cm<sup>3</sup>
- Used in 3G light sources
- Excellent thermo-mechanical properties

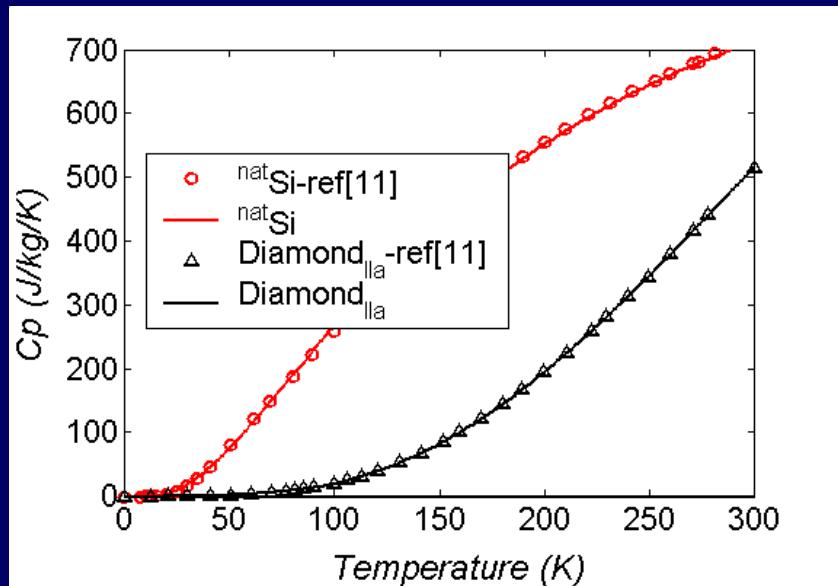
# Thermo-mechanical properties of the crystals



thermal deformation:  $\theta_{th} \sim \alpha/k$



# Thermo-mechanical properties of the crystals



Thermal diffusivity:  $D = \kappa / (\rho C_p)$

Thermal diffusion time:  $\tau_d \sim L^2 / D$

( $L \sim 1mm$ )

T (K)	thermal diffusivity ( $m^2/s$ )			thermal diffusion time ( $\mu s$ )		
	Si-nat	Si-28	Diamond	Si-nat	Si-28	Diamond
5	3.93	16.94	7.63	0.25	0.06	0.13
20	0.66	3.88	4.82	1.52	0.26	0.21
25	0.23	1.10	3.99	4.35	0.91	0.25
77	0.0035	0.0085	0.60	286	117	1.67
300	8.94E-05	0.000147	0.00195	11186	6801	512

# Time structure of X-ray sources

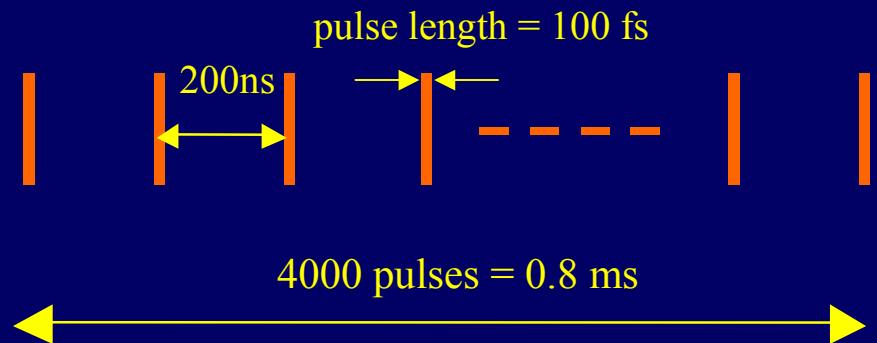
## ➤ Time structure in both Synchrotron Radiation and X-FEL

### ➤ Synchrotron radiation

- Very high repetition rate
- High average power

### ➤ X-FEL

- Extremely short pulse
- Extremely high peak power
- Low repetition rate
- Time scale varied from fs to s



Time-structure proposal  
of TESLA X-FEL  
(repetition rate 10 Hz)

# Time structure of X-ray sources

	units	TESLA	X-FEL	ESRF undulator U23	
		SASE 1	SASE 3	uniform	single-bunch
photon energy	keV	12.4	3.1	5.8*	5.8*
peak power P <sub>peak</sub>	W	2.40E+10	1.00E+11	3.76E+04	3.75E+06
average power P <sub>m</sub>	W	72	300	200**	20**
energy per pulse	mJ	1.8	7.5	0.000564	0.05632
energy per pulse train	J	7.2	30		
<b>pulse duration (FWHM)</b>	<b>ps</b>	<b>0.1</b>	<b>0.1</b>	<b>50</b>	<b>150</b>
number of pulse per pulse train		4000	4000		
time between pulse	ns	200	200	2.82	2816
<b>repetition rate</b>	<b>Hz</b>	<b>10</b>	<b>10</b>	<b>3.55E+08</b>	<b>3.55E+05</b>

\*fundamental energy

\*\*beam size 1mm x 1mm at 28 m from source, I<sub>uniform</sub>=200 mA, I<sub>single</sub>=20 mA

# Time structure of X-ray sources

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- **In synchrotron radiation**
  - The time structure is not considered in the optic design
  - The theoretical estimation of the monochromator performance using **average power** is in good agreement with experimental results  
(Zhang *et al.* 2003, 2001, Taijiri *et al.* 2001)
- **In this study, the pulse train structure of the X-FEL will be averaged as:**
  - a macro pulse of duration of 0.8 ms ( $4000 \times 200\text{ns} = 0.8\text{ ms}$ )
  - the repetition rate: 10 Hz
- *Transient heat transfer process of the 100 fs pulse of the X-FEL is very complicated and is not considered in this study*

# Cooling, geometry and power absorption

## ➤ Cooling

- Liquid-nitrogen cooling:  $h_{cv}=5000 \text{ W m}^{-2} \text{ K}^{-1}$ ,  $T_f=77 \text{ K}$
- Liquid-helium cooling: ( $h_{cv}=1000, 5000 \text{ W m}^{-2} \text{ K}^{-1}$ ,  $T_f=4 \text{ K}$ , technology to be developed)

## ➤ Crystal geometry

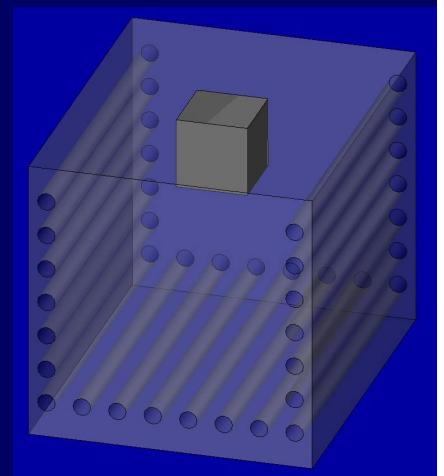
- rectangular shape
- 2 different sizes:
  - $120\text{mm} \times 60\text{mm} \times 60\text{mm}$  : to compare the effects of material properties
  - $20\text{mm} \times 20\text{mm} \times 20\text{mm}$  for single-isotope silicon-28 and diamond IIa

## ➤ Cooling scheme

- Side cooling (2 side surfaces), mostly used in 3G light sources
- 5-surfaces cooling: maximum cooled surface area
- Only crystal is modeled. An effective cooling coefficient is applied to the cooled surface

## ➤ Power absorption

- Surface
- volume



# Cooling, geometry and power absorption

## Absorption coefficients of the diamond and silicon crystals

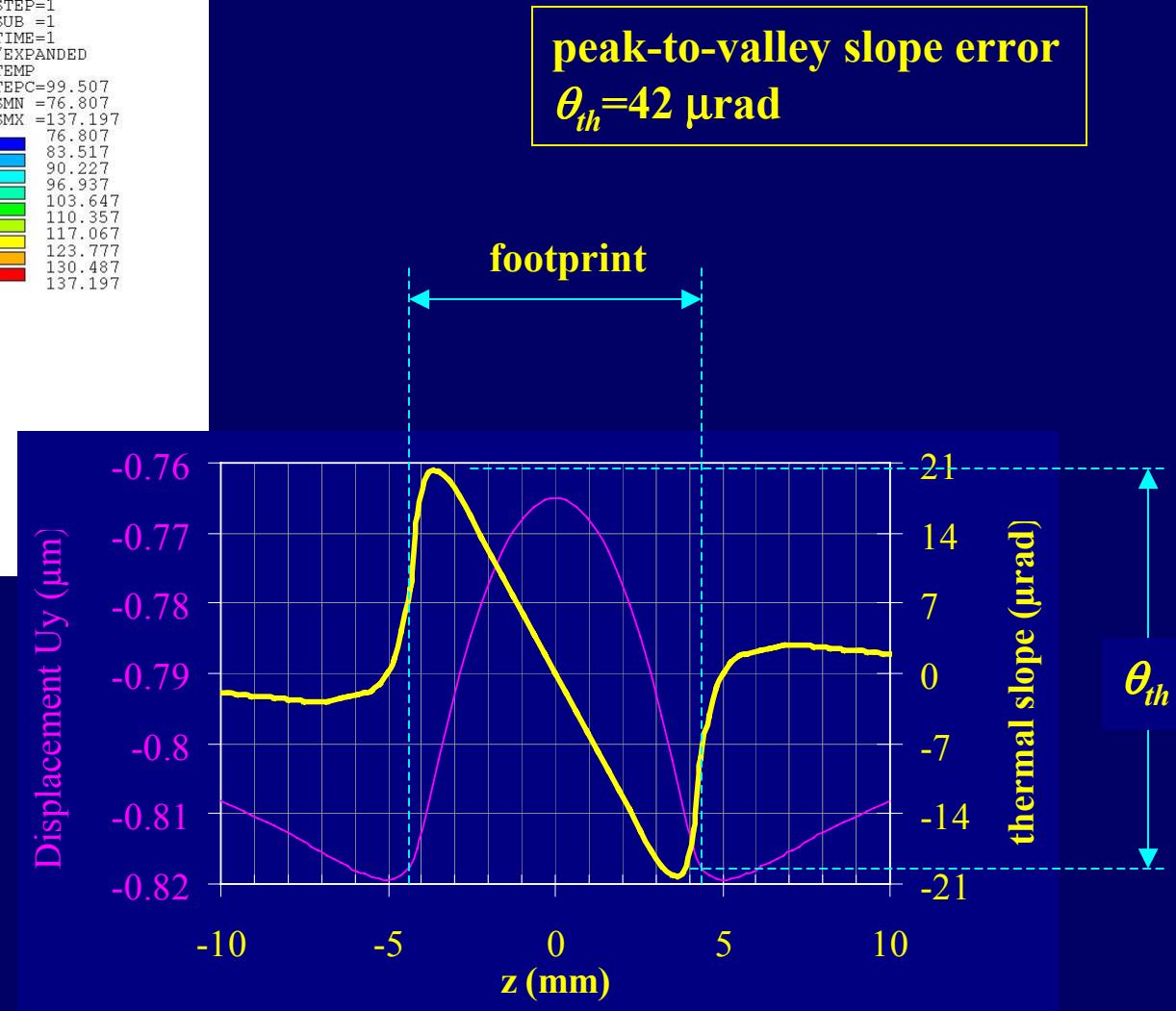
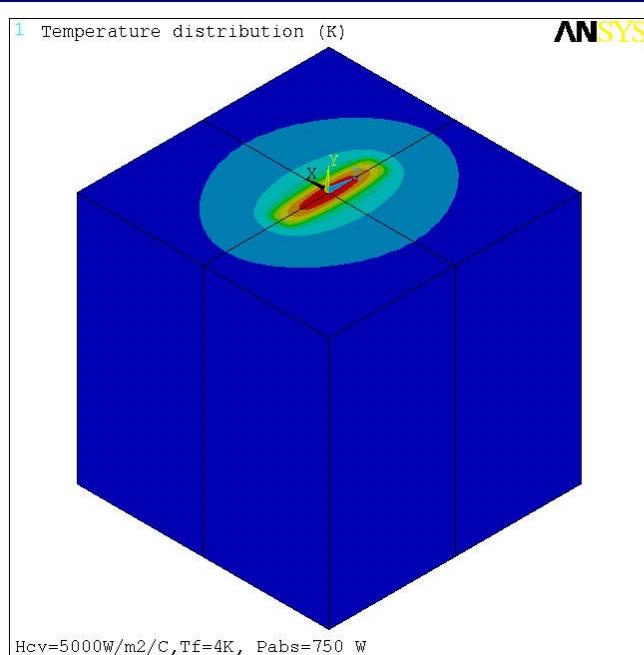
material	diamond	Silicon
Z	6	14
density	g cm <sup>-3</sup>	3.52
photon energy	keV	3.1      12.4
absorption coefficient $\mu$	mm <sup>-1</sup>	28.67      0.45
absorption length $\mu^{-1}$	mm	0.03      2.23
effective thickness in case of $\theta_{\text{Bragg}}=14^\circ$	mm	0.008      0.54      0.001      0.06

$E_{\text{ph}}=12.4 \text{ keV}$  from SASE 1

$E_{\text{ph}}=3.1 \text{ keV}$  from SASE 3

► **Surface absorption:** good approximation

# Thermal deformation in time-averaged mode



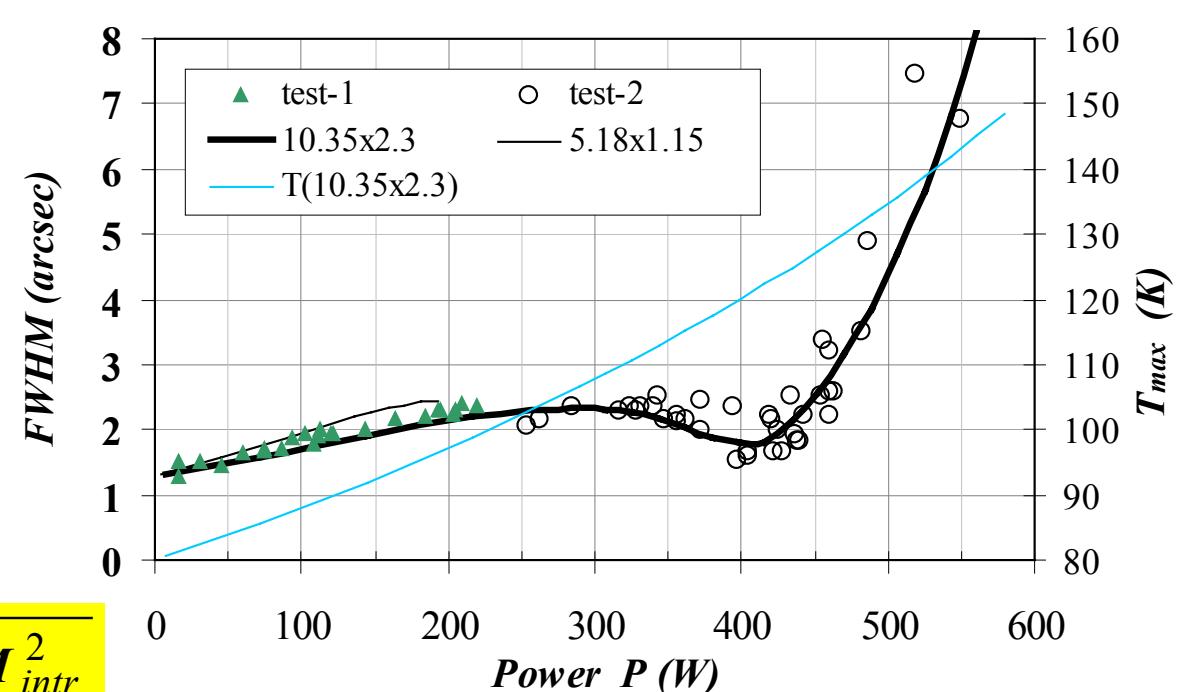
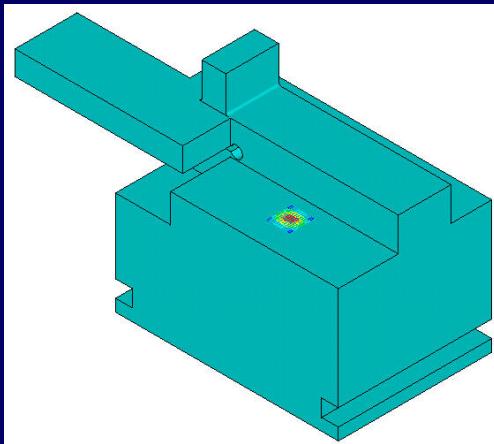
Single-isotope silicon-28 crystal:  
20mm x 20mm x 20mm

Beam size: 2mm x 2mm

Bragg angle: 14°

# Thermal deformation in time-averaged mode

Zhang, L., Lee, W.K., Wulff, M. & Eybert, L. (2003). *J. Synchrotron Rad.* **10**, 313-319



$$FWHM_c = \sqrt{(\theta_{th} + \theta_0)^2 + FWHM_{intr}^2}$$

$\theta_{th}$ : thermal slope error from FEA

$\theta_0$ : initial deformation due to mounting/fabrication induced strain

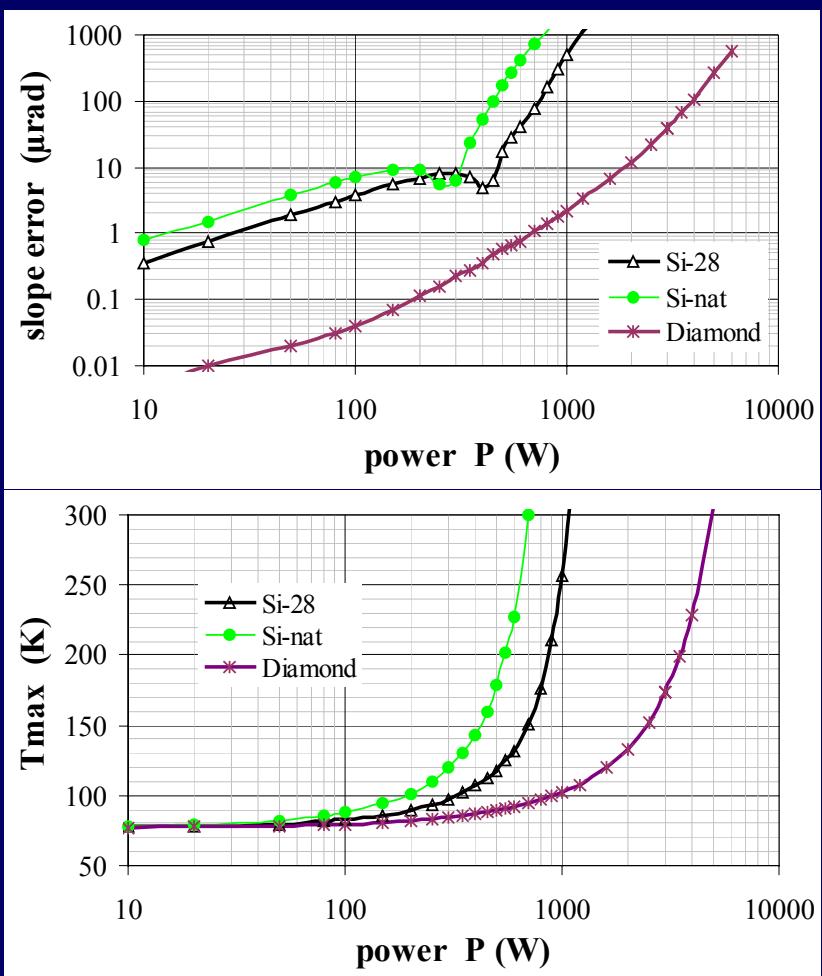
**Figure 8**

Rocking curve width FWHM as well as maximum temperature on the channel-cut Si crystal versus total absorbed power. 10.35x2.3 and 5.18x1.15 denote calculated results with corresponding beam sizes.

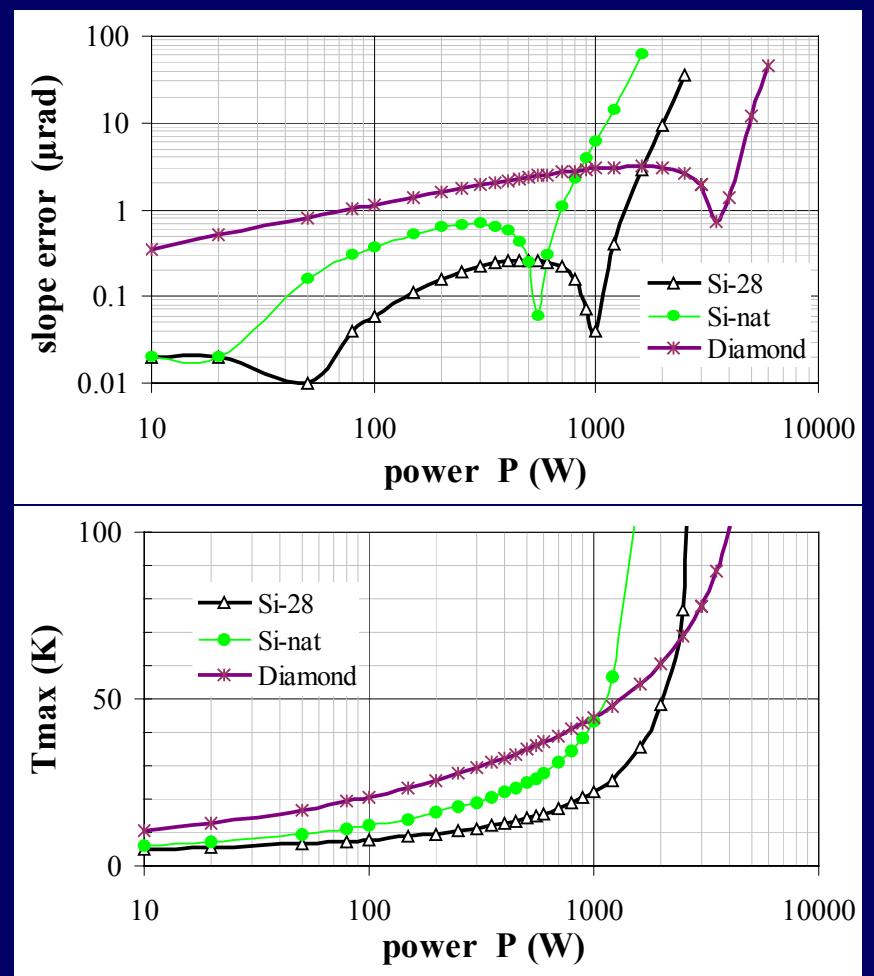
# Thermal deformation in time-averaged mode

Crystal size: 120mm (L) x 60mm (W) x 60mm (T), side-cooling coefficient  $h_{cv} = 5000 \text{ W m}^{-2} \text{ K}^{-1}$

Liquid-nitrogen cooling ( $T_f=77 \text{ K}$ )

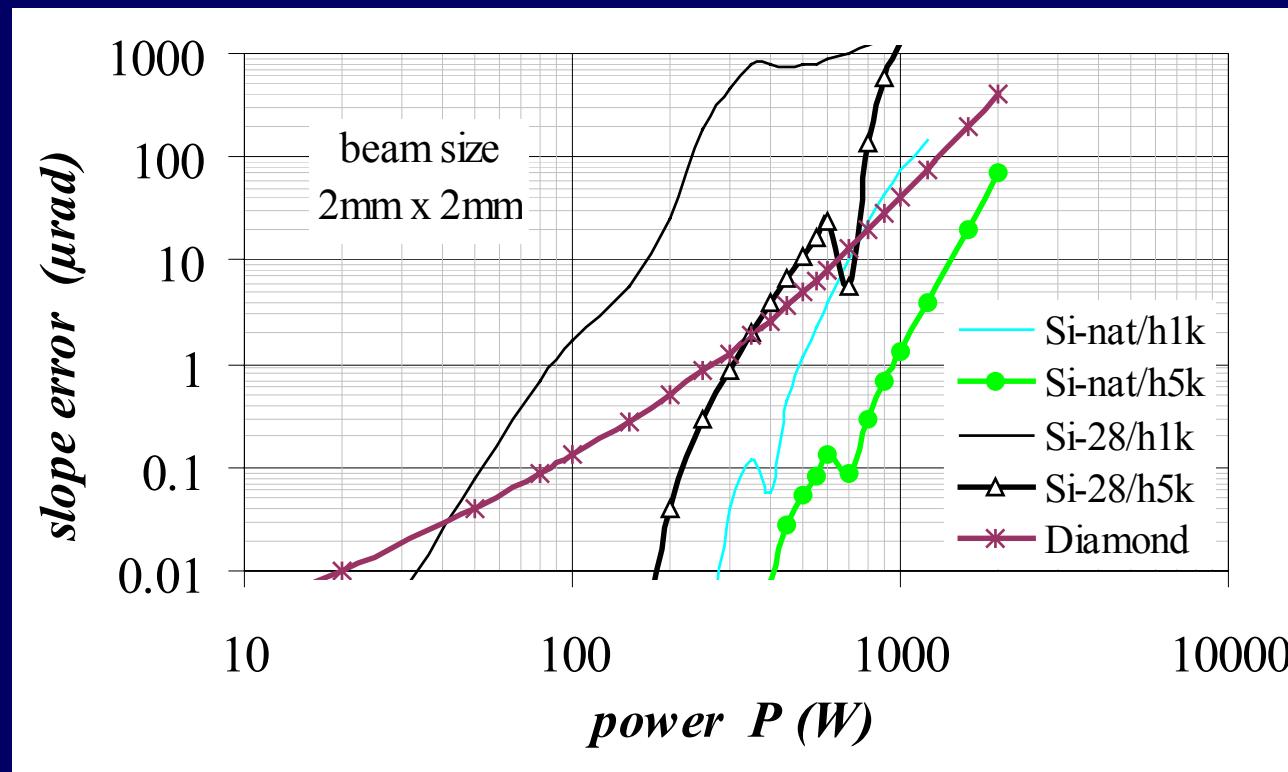


Liquid-helium cooling ( $T_f=4 \text{ K}$ )



# Thermal deformation in time-averaged mode

- Liquid-nitrogen-cooled diamond crystal (20mm x 20mm x 20mm)
- Liquid-helium-cooled single-isotope silicon-28 crystal (20mm x 20mm x 20mm)
- Liquid-helium-cooled natural silicon crystal (120mm x 60mm x 60mm)
- Five surface cooling



# Time-dependent temperature and thermal slope

## ➤ 3 crystals:

- Liquid-nitrogen-cooled diamond crystal (20mm x 20mm x 20mm)
- Liquid-helium-cooled single-isotope silicon-28 crystal (20mm x 20mm x 20mm)
- Liquid-helium-cooled natural silicon crystal (120mm x 60mm x 60mm)

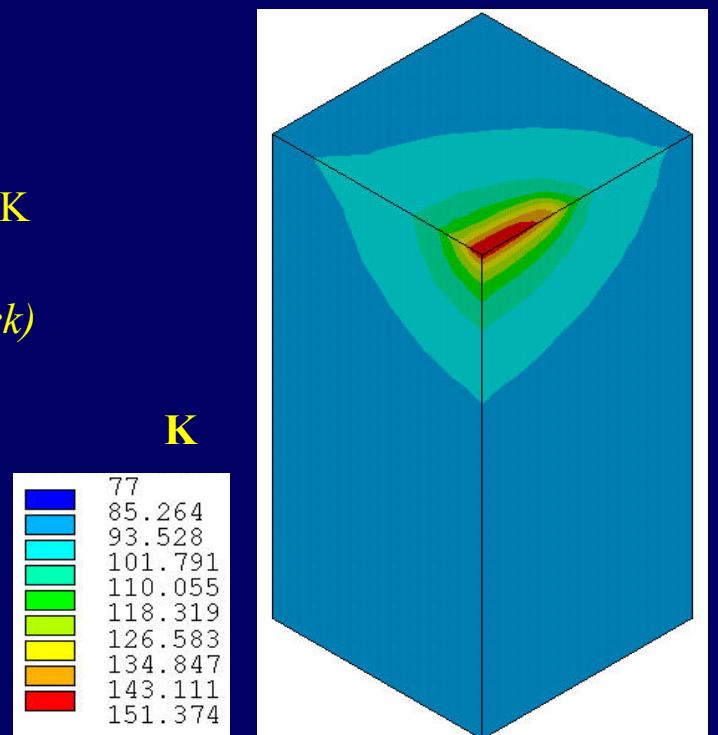
## ➤ Heat load (X-FEL)

- 0.8 ms pulse train → a macro pulse of 0.8 ms duration, repetition rate 10 Hz
- $Q=2 \text{ J} \rightarrow P_{\text{pulse-train}}=2.5 \text{ kW}, P_{\text{average}}=20 \text{ W}$
- Beam size: 2mm x 2mm, Bragg angle 14 °

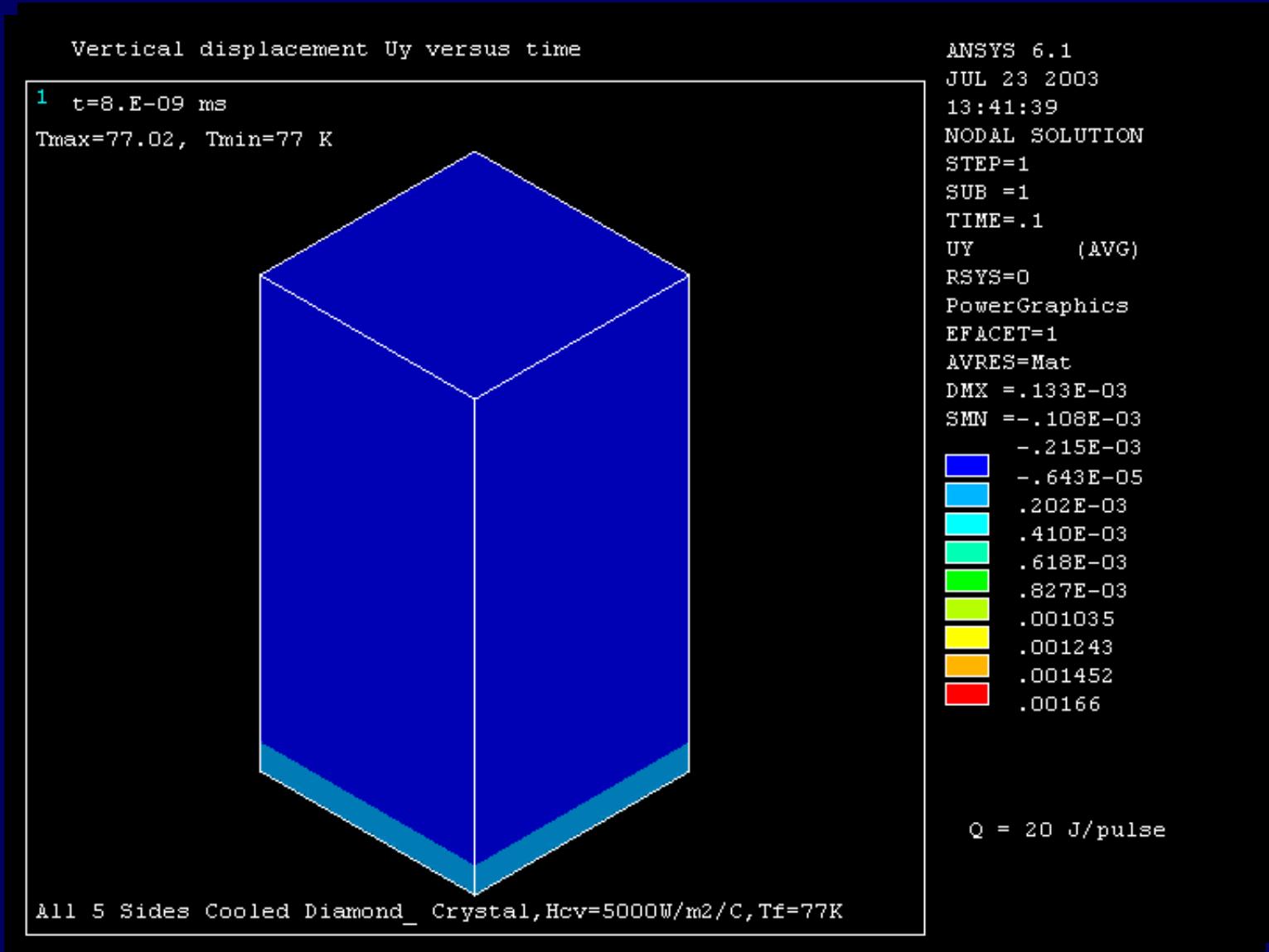
## ➤ Cooling

- Liquid-nitrogen cooling:  $h_{cv}=5000 \text{ W m}^{-2} \text{ K}^{-1}$ ,  $T_f=77 \text{ K}$
- Liquid-helium cooling:  $h_{cv}=5000 \text{ W m}^{-2} \text{ K}^{-1}$ ,  $T_f=8 \text{ K}$   
*(convergence, temperature gradient in the cooling block)*

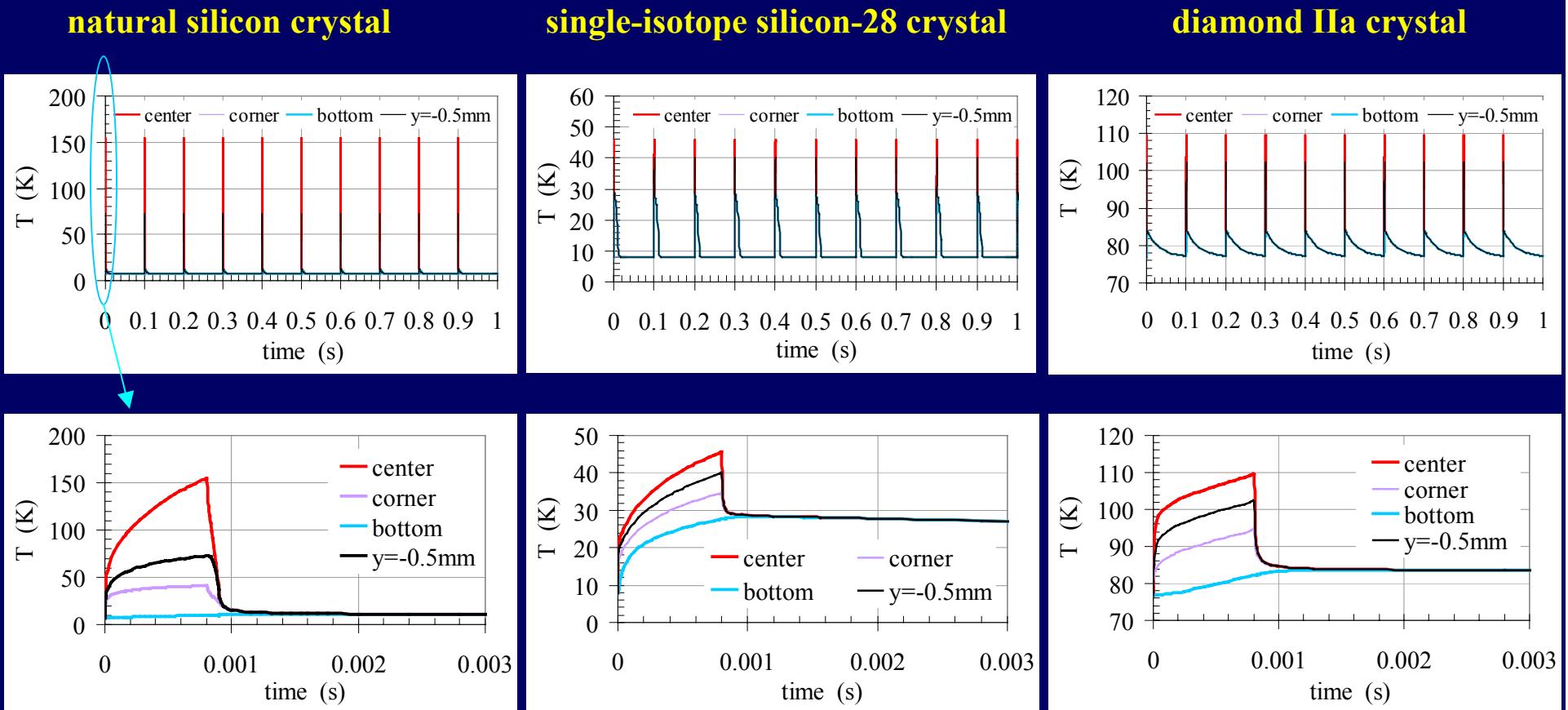
Temperature distribution of the liquid-nitrogen-cooled diamond crystal at 0.8ms (the end of pulse train),  $Q=4 \text{ J}$



# Time-dependent temperature and thermal slope



# Time-dependent temperature and thermal slope



- Temperature variation: 10-Hz repetition rate
- No cumulating effect (especially in Silicon)
- Very short time for temperature to go to uniform

# Time-dependent temperature and thermal slope

$$Q = m \int_{T_f}^T C_p(T) dT$$

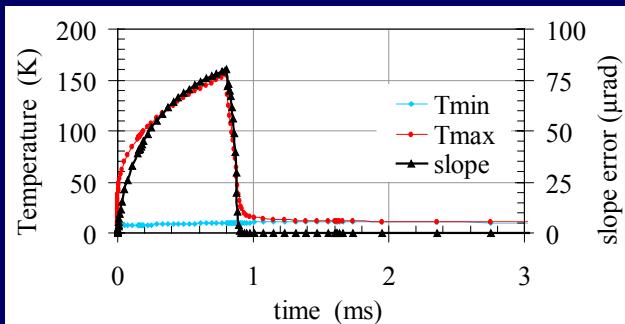
- Small cooled surface area
- Short time for temperature uniformization
- Not very high temperature rise ( $T - T_f$ )

→ analytical integration  $T_{\text{uniform}}$

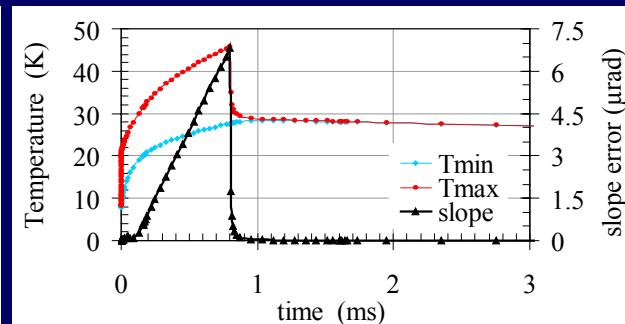
	size <i>mm X mm X mm</i>	$T_f$ <i>K</i>	$T_{\max}$ <i>K</i>	FEA <i>K</i>	analytical <i>K</i>	$\epsilon$	$t_{\text{uniform}}$ <i>ms</i>
natural silicon	120 x 60 x 60	8.0	154.6	<b>8.9</b>	<b>12.4</b>	<b>40%</b>	5.20
single-isotope silicon-28	20 x 20 x 20	8.0	45.7	<b>28.5</b>	<b>29.3</b>	<b>2.7%</b>	0.23
Diamond IIa	20 x 20 x 20	77.0	109.4	<b>84.1</b>	<b>84.1</b>	<b>-0.02%</b>	0.26

# Time-dependent temperature and thermal slope

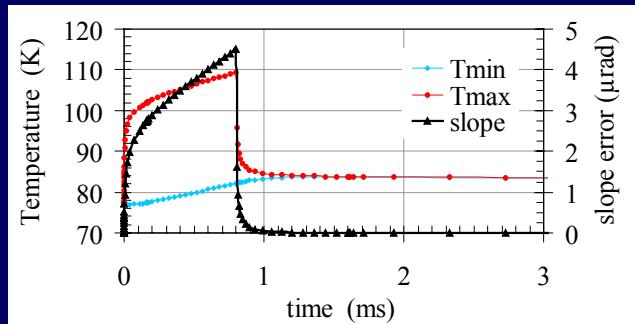
natural silicon crystal



single-isotope silicon-28 crystal



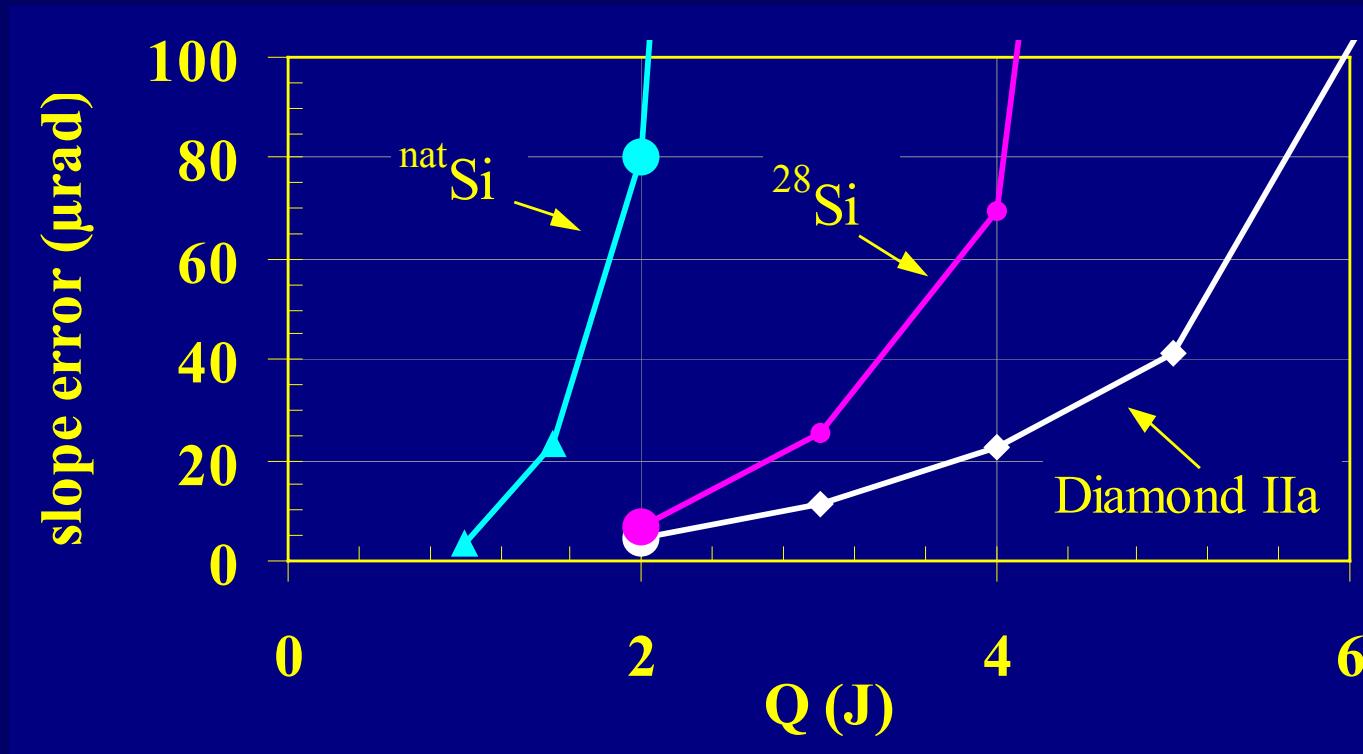
diamond IIa crystal



- Thermal slope increases with pulse train arrival
- Thermal slope drops to zero very shortly after the end of pulse train with Temperature uniformization

$\theta_{th}$ (μrad)	natural silicon	single-isotope silicon-28	Diamond IIa
Macro pulse, 0.8ms, $Q=2J$ , $P_{pulse}=2500$ W, $P_{average}=20$ W	80.1	6.8	4.5
continuous power $P=2500$ W		> 1000	
continuous power $P=20$ W		< 0.01	

# Time-dependent temperature and thermal slope



# Concluding remarks

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- **Under TESLA X-FEL beams**
  - The temperature and thermal deformation increase/decrease by following the pulse train, with a repetition rate of 10 Hz
  - For same average power,  $(\Delta T, \theta_{th})_{X-FEL} \gg (\Delta T, \theta_{th})_{X-SR}$
  - The time structure of the X-FEL has to be considered in the optic design
- **To limit the deformation induced by the X-FEL in crystal monochromators**
  - Liquid-nitrogen-cooled diamond IIa
  - Liquid-helium cooled single-isotope silicon-28
- **For continuous heat load, liquid-helium-cooled natural silicon is very competitive (large size, performance, cost effective)**
  - for  $\theta_{th} \leq 10 \mu\text{rad}$ ,  $P \leq 1400 \text{ W} / 2\text{mm} \times 2\text{mm}$ , liquid-helium-cooled 120mm x 60mm x 60 mm natural silicon
- **For the X-FEL crystal monochromator, the power absorption and heat transfer in sub-picosecond time scale should also be studied in details**
- **Liquid-helium cooling technology to be developed**